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Research papers

Temporal variations of runoff and sediment load in the upper Yellow River, China

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ABSTRACT

Operations of amount of large and medium reservoirs have remarkably changed runoff and sediment loads, and consequently affected the fluvial processes intensively on the upper Yellow River. In this study, time series of runoff and sediment transport rates of four major hydrological stations on the upper Yellow River were used to analyze temporal and spatial variations of runoff and sediment loads. Mann-Kendall test and wavelet analysis were applied to analyze the datasets. Temporal variations in runoff and sediment loads were discerned in terms of changing trend, abrupt change year, and multi-periods from the time series. Additionally, a time series of runoffs was reconstructed based on a modeling scenario removing impact of reservoir impoundment and water diversion to indicate the status without human disturbances. Comparison of the measured and reconstructed datasets was conducted to evaluate the impact of reservoir impoundment and water diversion on hydrological variations. The measured runoff and sediment loads showed obvious decreasing trends due to impoundment and water diversion. However, the reconstructed runoffs regarded as only affected by climate change showed no significant changing trend at a 95% confidence level, confirming that, instead of climate change, human activities played the most important roles in variations. The measured datasets indicated that the reservoir construction and operation caused an abrupt change in runoff in 1986, while the reconstructed datasets indicated another abrupt change in 1995. Wavelet transform analysis distinguished the multi-periodical features of the time series. The first, second, and third dominant periodicities of the measured runoffs were 25–27, 16, and 8 years, respectively, whereas the first three dominant periodicities of the reconstructed runoffs were 26–31, 12, and 7 years, respectively. It was indicated that the high-frequency periodicities of runoffs decreased while the low-frequency periodicities increased, owing to reservoir impoundment and water diversion.

1. Introduction

Rivers are efficient conveyors of water and sediment from headwaters to the sea (Williams, 2012). In recent years, studies of riverine sediment flux to oceans, and their sediment transport processes have received greater attention related to climate change and human activities in river basins all over the world (Walling and Fang, 2003; Syvitski et al., 2005; Wang et al., 2007). Consequently, many large river deltas have retreated and their inhabitants have become increasingly vulnerable. Among world large rivers, the Yellow River provides an excellent illustration of the interactions among climate change, extensive soil and water conservation, hydropower development, and sediment control measures (Walling, 2006). Flood-vulnerable delta surface areas could increase more than 50% because of increased sediment trapping at upstream reservoirs and engineered floodplains, combined with rising global sea level (Syvitski et al., 2009). Over the past 150 years, the Yellow River has been the most heavily loaded in the world, creating the mega Yellow River Delta, prograding into the epicontinental Bohai Sea. However, the delta has been starved and has retreated, owing to the declining of water and sediment supply since 1995 (Wang et al., 2007). The annual mean of sediment discharge has decreased from 1.6 billion tons/yr to < 10 million tons/yr. This has decreased riverine nutrients and total dissolved solids, causing many aquatic ecosystems in the lower reaches and coastal regions to experience significant changes in biodiversity and biotic integrity (Chen et al., 2005).

Quantitative analysis of the spatial and temporal variation of streamflow and sediment load provides a good reference for flood mitigation, river channel stabilization, and river basin and delta management (Zhao et al., 2014). Much attention has been paid to the middle reach of the Loess Plateau, which is the source of nearly 90% of

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the aforementioned sediment load. Formerly, sediment suspensions in the river's lower reaches triggered enormous flood catastrophes, owing to the release of heavy sediment loads from the Loess Plateau (Wang et al., 2016). Comprehensive studies have analyzed variations in runoff and sediment loads in the middle and lower reaches. Wang et al. (2016) showed that reduced sediment transport in the Yellow River was caused by changes in water discharge and sediment concentration, both influenced by regional climate changes and human activities over the Loess Plateau. Since the 1970s, landscape engineering, terracing, and check-dam and reservoir construction were the primary factors driving sediment reduction. In addition, large-scale vegetation restoration projects have also reduced soil erosion since the 1990s (Yao et al., 2017).

Apart from the major sediment yield region on the Loess Plateau, the upper Yellow River, the main runoff-producing region, accounting for more than 50% of the total annual runoff, has lost attention because fewer human activities have been performed there, compared to the lower reach. However, the thirteen large and many more medium reservoirs have been constructed since 1960 on the stem and tributaries of the upper Yellow River, including the Qingtongxia, Liujiaxia, Sanshenggong, Longyangxia, etc. The reservoirs are beneficial for irrigation and flood defense, and they have changed the runoff and sediment loads to their downstream reaches, impacting fluvial processes. Owing to reservoir operations on the upper Yellow River, upstream reservoirs have experienced sedimentation, and bankfull discharges have decreased sharply since the 1990s (Shen et al., 2007). Simultaneously, with recent land-use changes and the implementation of water and soil conservation projects, runoff and sediment loads have also dramatically decreased. In the Loess Plateau, the sediment load decreased by approximately 90% over the past 60 years (Wang et al., 2016). All changes in the upper Yellow River will eventually influence changes in the lower reaches. Facing this situation, to help manage the river basin, more attention should be given to figuring out how the discharges of water and sediment change the main runoff-yield regions.

Most of the earth's largest rivers suffer from anthropological disturbances. Our major concern is whether human activities play an important role in causing hydrological variations to large rivers. The objectives of this study are to illustrate the inter-annual and monthly variations in runoff and sediment loads in the upper Yellow River, and to reveal the impact of basin-wide human activities (e.g., dams and reservoirs, soil conservation practices, and water abstractions). This study leverages datasets recorded at all gauging stations on the upper Yellow River bwteen 1950 and 2014. We use the full descriptions of temporal and periodic variations of runoff and sediment loads. Additionally, we discuss the effects of reservoirs and water diversions on the runoff and sediment load variations, compared to between the measured time series of runoffs, sediment transports, and reconstructed data, based on a modeling scenario removing the impact of reservoir impoundment and water diversion.

2. Study area and methods

2.1. Study area

This study focuses on the upper Yellow River from the Ningxia Province to the Inner Mongolia, stretching about 1000 km from Xiaheyan in the Ningxia Province to Toudaoguai in Inner Mongolia (Fig. 1). Hydrological stations (i.e., Lanzhou, Xiaheyan, Qingtongxia, Shizuishan, Bayangaole, Sanhuhekou, and Toudaoguai) have recorded discharges of water and sediments in the upper reach since 1950. The Lanzhou Station was the first hydrological station downstream of the Liujiaxia Dam. Thus, its records help evaluate the dam effect and improve our analysis. Downstream of Xiaheyan Station, the river flows to the northeast in the Ordos Plateau. Then, it enters the Yinchuan and Hetao plains, passing through the Tengger Desert, Hedong Sandy, Ulan buh Desert, and the Kubuqi Desert, ending at Toudaoguai Station. Large irrigation projects, including the Weining, Qingtongxia, and Hetao irrigations, are located in this region. They rely on water supplies from the upper Yellow River.

2.2. Data

We obtained continuous time series data of daily runoff and sediment loads of hydrological stations from the Yellow River Conservancy Commission, Ministry of Water Resources, China. Table 1 summarizes the basic information from these datasets. According to the statistical analyses of the gauge station datasets and considering the locations, four representative stations were selected for further analysis: Xiaheyan Station on the province boundary between Gansu and Ningxia; Shizuishan Station on the province boundary between Ningxia and Inner Mongolia; Sanhuhekou Station in Inner Mongolia; and Toudaoguai Station, the most downstream station.

In addition to the measured datasets, a time series of runoffs was constructed based on the modeling scenario removing the impacts of reservoir impoundment and water diversion for agricultural irrigation and urban industry along the upper Yellow River, performed by the Hydrology Bureau of the Yellow River Conservancy Commission. Equation (1) is applied in the reconstruction of the hydrological series:

$$Q_{res} = Q_0 + (Q_{in} - Q_{out}) + (Q_{div} - Q_{rtn}) \quad (1)$$

where Q_{res} is the reconstructed discharge, Q_0 is the measured discharge, Q_{in} is the discharge flowing into a reservoir, Q_{out} is the discharge out of the reservoir, Q_{div} is the water diversion, and Q_{rtn} is the water return to the river channel. Analysis of the variation trend, abrupt changes

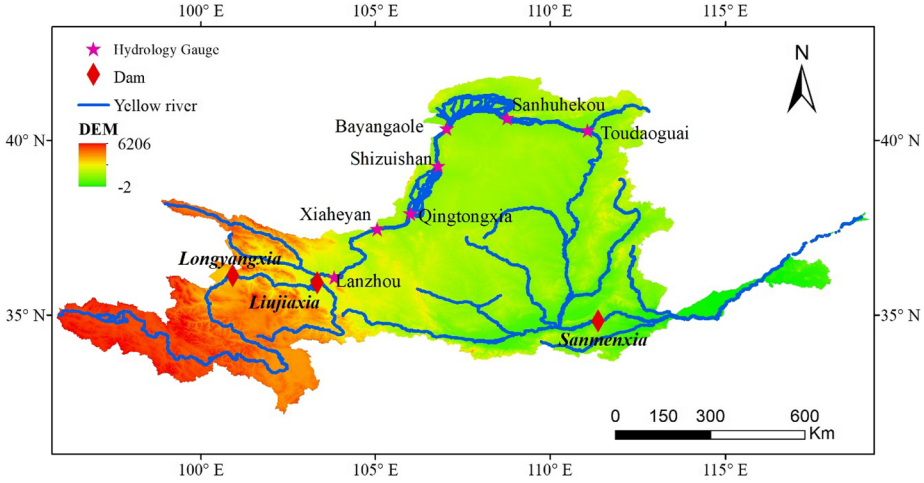

Fig. 1. Yellow River basin and its hydrology gauge stations: Lanzhou, Xiaheyan, Qingtongxia, Shizuishan, Bayangaole, Sanhuhekou, and Toudaoguai. The large dams Longyangxia, Liujiaxia, and Sanmenxia are indicated. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Basic information from the measured datasets.

Stations	Distance from the Headwater of the Yellow River (km)	Controlled Area (10^4 km^2)	Dataset Period	Mean annual runoff (10^8 m^3/a)	Mean annual sediment load (10^8 tons/a)
Lanzhou	1988.05	22.25	1935–2014	316.85	0.606
Xiaheyan	2292.08	25.41	1951–2014	291.97	1.015
Qingtongxia	2428.86	27.50	1954–2014	236.62	0.988
Shuizuishan	2649.31	30.91	1943–2014	278.18	1.048
Bayangaole	2812.29	31.40	1956–2014	210.79	0.945
Sanhuhekou	3042.75	34.79	1953–2014	218.23	0.951
Toudaoguai	3318.16	36.79	1952–2014	211.42	0.945

during the year, and the periodicity of the measured and reconstructed datasets indicate the impacts to reservoirs and water diversion on the hydrological variation of the upper Yellow River. The sediment loads cannot currently be reconstructed using the above formula, because channel scouring usually occurs downstream from the reservoir, owing to sediment trapping.

2.3. Data proceeding methods

Trend testing has determined that the values of random variables generally increase or decrease over a statistical period (Hirsch et al., 1982). A combination of statistical tests, hydrological modeling, and land-use maps has proven effective for studying the temporal trends and abrupt changes in runoff and sediment loads in the river reach past the Loess Plateau (He et al., 2013; Zhao et al., 2014; Zuo et al., 2016). Therefore, the Mann–Kendall (MK) tests (Mann, 1945; Kendall, 1975) and wavelet analyses are combined and applied to advance the datasets and to distinguish the variation features of the runoff and sediment loads in terms of changing trends, abrupt changing years, and periodicities.

(1) Mann Kendall test

The MK test is a the rank-based nonparametric test for assessing a trend's significance and it is widely used to evaluate changing trends and discontinuities in agro-meteorological and hydrological time series (Hamed, 2009; Neeti and Eastman, 2011; Shadmani et al., 2012; Chattopadhyay et al., 2012). With MK, if a trend is present, the sign values will either increase, or decrease constantly (Nishioka and Takara, 2004; Burn and Hag Elnur, 2002).

The MK test is based on the correlation between the ranks of a time series and their time order. For a time series X = {x1, x2, …, xn}, the test statistic is given by (Ozgur and Murat, 2014):

$$s = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn(x_j - x_i) \tag{2}$$

where n is the length of the time series, and the value of $sgn(x_j - x_i)$ was computed using the following formula:

$$sgn(x_i - x_j) = \begin{cases} 1 & x_j - x_i > 0 \\ 0 & x_j - x_i = 0 \\ -1 & x_j - x_i < 0 \end{cases} \tag{3}$$

When n is large enough ($n > 10$), the statistic S tends toward normality with mean $E(S)$ and variance $Var(S)$ defined as the follows:

$$E(S) = 0$$

$$Var(S) = \frac{n(n-1)(2n+5) - \sum_{p=1}^{q} t_p(t_p-1)(2t_p+5)}{18} \tag{4}$$

where t_p is the number of ties for the p^{th} value and q is the number of tied values (i.e., equal values).

The standardized test statistic Z was calculated according to the following expression:

$$Z = \begin{cases} (S-1)/\sqrt{Var(S)} & S > 0 \\ 0 & S = 0 \\ (S+1)/\sqrt{Var(S)} & S < 0 \end{cases} \tag{5}$$

The calculated Z value was compared with the standard normal distribution table with two-tailed confidence levels ($\alpha = 0.01$, $\alpha = 0.05$). The null hypothesis (H_0) is invalid when $|Z| > |Z_{1-\alpha/2}|$, and thus the trend is statistically significant; otherwise, the H_0 hypothesis is accepted that the trend is not statistically significant, and there is no trend in the time series (Ozgur and Murat, 2014). A positive Z value indicates an increasing trend in the time series, while a negative value indicates a decreasing trend. In this study, we applied a significance level of $P = 0.05$, so the increasing or decreasing trend will be accepted at a 95% confidence level.

The MK test was also used to determine the abrupt changing year for time series. The statistic S_k of the abrupt change test was calculated as following: $S_k = \sum_{i=1}^{k} r_i$

$$r_i = \begin{cases} +1, (x_i > x_j), \\ 0, (x_i \le x_j), \end{cases} j = 1, 2, \cdots, i \tag{6}$$

Then, the parameter UF_k was computed using the following expression:

$$UF_k = \frac{S_k - E(S_k)}{\sqrt{\mathrm{var}(S_k)}} \tag{7}$$

Its mean and variance were determined by the equations:

$$E(Sk) = \frac{k(k-1)}{4}$$

$$Var(S_k) = \frac{k(k-1)(2k+5)}{72} \tag{8}$$

where $k = 1, 2, 3 \ldots n$. Then, the time series will be ranged with inverted sequence, and all the steps will be repeated. The parameter UB_k was computed similarly to UF_k. The curves of UB_k and UF_k were obtained in Cartesian coordinates, and the intersection points falling in the range of -1.96 and 1.96 (at 95% confidence level) were regarded as the abrupt change points.

(2) Wavelet analysis

The wavelet transform shows large advances in signal processing, attracting much attention since its theoretical development in 1984 (Grossman and Morlet, 1984). An exploration of the wavelet transform, as applied to daily river discharge records, demonstrates its strong potential for quantifying stream-flow variability equal for both periodic and non-periodic features. Furthermore, their locations in time are preserved (Smith et al., 1998). Wavelet transform analysis appears to be an effective tool for examining nonstationary and multiscale time series and transient phenomena in hydrological processes (Labat et al., 2005). Consequently, considerable information can be obtained about the

modes of a particular signal without losing information about when the modes occurred or how variable they were (Benson and Daggett, 2012).

The continuous wavelet transform (CWT) is defined as the sum over time of the real signal, $x(t)$, multiplied by the scaled (stretched or compressed) shifted versions of the wavelet function, ψ (Nakken, 1999).

$$X(a, b) = \frac{1}{\sqrt{|a|}} \int_{-\infty}^{+\infty} x(t)\psi\left(\frac{t-b}{a}\right)dt \quad (9)$$

where the wavelet coefficients, X, are the result of the CWT of signal $x(t)$. The function, $\psi(t)$, can be real or complex, playing the role of a convolution-kernel (i.e., a wavelet). The scale or dilation parameter, a, scales a function by compressing or stretching it, whereas b is the translation of the wavelet function along the time axis.

The wavelet analysis signal highly correlates to the wavelet type. The Morlet wavelet is a periodic function enveloped by a Gaussian function and is widely used to identify periodic oscillations of real-life signals (Issac et al., 2004; Labat, 2005). Complex wavelet functions are effective at avoiding amplitude zero crossings in the time and frequency domains (Dziedziech et al., 2015). Therefore, in this study, the complex Morlet wavelet function is applied to distinguish temporal runoff oscillations, following numerous previous successful applications related to time-variant and nonlinear dynamic systems (Zhang et al., 2004). Using wavelet transform, wavelet coefficients and their variances are calculated. Wavelet power spectra and multi-scale periodicity features are obtained with wavelet coefficients. The shapes of wavelet spectra are controlled by the distribution of event time-scales, which in turn reflect the timing, variability, and the mechanism of water delivery to the river (Smith et al., 1998).

3. Results

(1) Variation trends in the measured datasets of runoff and sediment load

The full records of daily runoff and sediment transport rates at the given stations are shown in Fig. 2. Generally, high discharge and high sediment loads occur over the summer from the upstream to the downstream of the upper Yellow River. Moreover, the lower reach of the Shizuishan showed spring peaks of runoff and sediment loads, especially during peach-blossom time, probably owing to snow and ice melting. For each station, the runoff and sediment load during flood seasons decreased noticeably since 1970. Since 1990, the natural distribution of runoff during flood season has totally changed, and the discharge during non-flood seasons has dominated, accounting for more than 60% of the annual runoff. Sediment loads in flood season have also decreased significantly, especially downstream.

As shown in Fig. 3, the annual average runoff of the Xiaheyan, Shizuishan, Sanhuhekou, and Toudaoguai stations from 2000 to 2014 was 24.99, 21.96, 15.95, and 15.37 billion m^3/yr, respectively, accounting for only 64.8–81.6% of the annual averages of these stations from 1950 to 1959. The annual average sediment load from 2000 to 2012 decreased to 0.041, 0.058, 0.053, and 0.043 billion tons/yr at the four corresponding stations, respectively, accounting for only 17.5–37.1% of the annual averages from 1950 to 1959. From 1950–1989, the sediment load at Xiaheyan Station was 1.84 times higher than Lanzhou Station, upstream, which was not remarkably different from downstream stations (i.e., Shizuishan and Toudaoguai). The decreased runoff rate in the Toudaoguai station was largest among the four hydrologic stations, caused by less supplementary water and greater water diversion upstream. The decrease of sediment load in the Xiaheyan gauge station was the largest, because of the reservoir sediment storage. In the following sections, the datasets of the representative stations are analyzed to show variations of hydrological features.

The MK test indicates decreasing trends in the time series of runoff and sediment loads of the representative stations (see Table 2). All Z values are negative with confidence values < 0.01, indicating that the runoff and sediment load decreases significantly on the upper Yellow River. The absolute Z values of sediment load are higher than those of the runoff, indicating that the reduction in sediment load is more notable. The absolute Z value of runoff is minimal at Xiaheyan Station, and is maximal at Toudaoguai Station, indicating that the reduction of runoff in the lower reach of the upper Yellow River was more remarkable than that at the upper reach. Regarding the water and sediment trapped by reservoirs upstream of the Xiaheyan station, with less supplemental water along the river and greater water diversion, runoff decreased from the upstream to the downstream, and the decreasing rate was most notable at the downstream station: Toudaoguai.

However, the absolute Z value of sediment load was the maximal at the Xiaheyan station, not the Toudaoguai station, implying that the channel bed was scoured by clear or low sediment-laden water flow released from upstream reservoirs. The eroded bed materials were added to the water flow, supplementing the sediment concentration downstream. Therefore, the decreased rate downstream was smaller than that of upstream. Previous studies indicate that, after the impoundment of the Longyangxia and Liujiaxia reservoirs, the channel bed of the downstream varied remarkably because of reservoir impoundment and clean-water/ low-sediment load flow release (An et al., 2018). Moreover, at the Xiaheyan section closest to the reservoir, the lowest sediment concentration and transport occurred. Thus, from Xiaheyan to Shizuishan, the channel bed mainly experienced scouring, whereas along the lower reach, from Bayangaole to Toudaoguai, the channel bed mainly experienced sedimentation (Tian et al., 2013; An et al., 2018).

(2) Abrupt changes of measured runoff and sediment load datasets

The results of abrupt change testing in terms of years of the time series of runoff and sediment loads for the representative stations, are shown in Table 3. Abrupt changes did not occur synchronistically for the runoff and sediment loads. The abrupt changing years differed for runoff and sediment load series for the different stations. Abrupt changes for the annual runoff occurred in 1986 for all stations, when the Longyangxia Reservoir was constructed and put into combined operation with the Liujiaxia Reservoir. Both the storage and regulation capacities of the Longyangxia were larger than Liujiaxia. The reservoir capacities were large enough to change the annual runoff and its temporal distribution within a year. Additionally, water diversion increased greatly, owing to industrial development and urbanization after 1986. According to the measurement by the Hydrology Bureau of the Yellow River Conservancy Commission during the period 1986–2014, the annual average water diversion from the section of Xiaheyan-Toudaoguai was up to 12.56 billion m^3/yr. Thus, the runoff was discontinuous since 1986.

An abrupt change in annual sediment occurred in a disorderly fashion along the reach, asynchronously with runoff. The variation of sediment load was more complex, compared to the runoff. For instance, an abrupt change was identified in 1989 at Xiaheyan, and in 1986, 1978, and 1982 at Shizuishan, Sanhuhekou, and Toudaoguai, respectively.

The monthly average runoff discharge and sediment-load distribution curves of the entire recorded period, before and after the abrupt changing year, are plotted in Fig. 4. At all stations, the highest discharges and sediment loads (i.e. equal or exceeding 1% and 10%) decreased significantly after 1986, compared to those beforehand. The peaks of discharge and sediment loads were reduced by about 50%. Additionally, all high discharges and sediment loads with percentages of 1–40% decreased remarkably after 1986. However, variations of low discharges and sediment loads with percentages equal or exceeding 50% were gentle and incomparable to variations of higher ones.

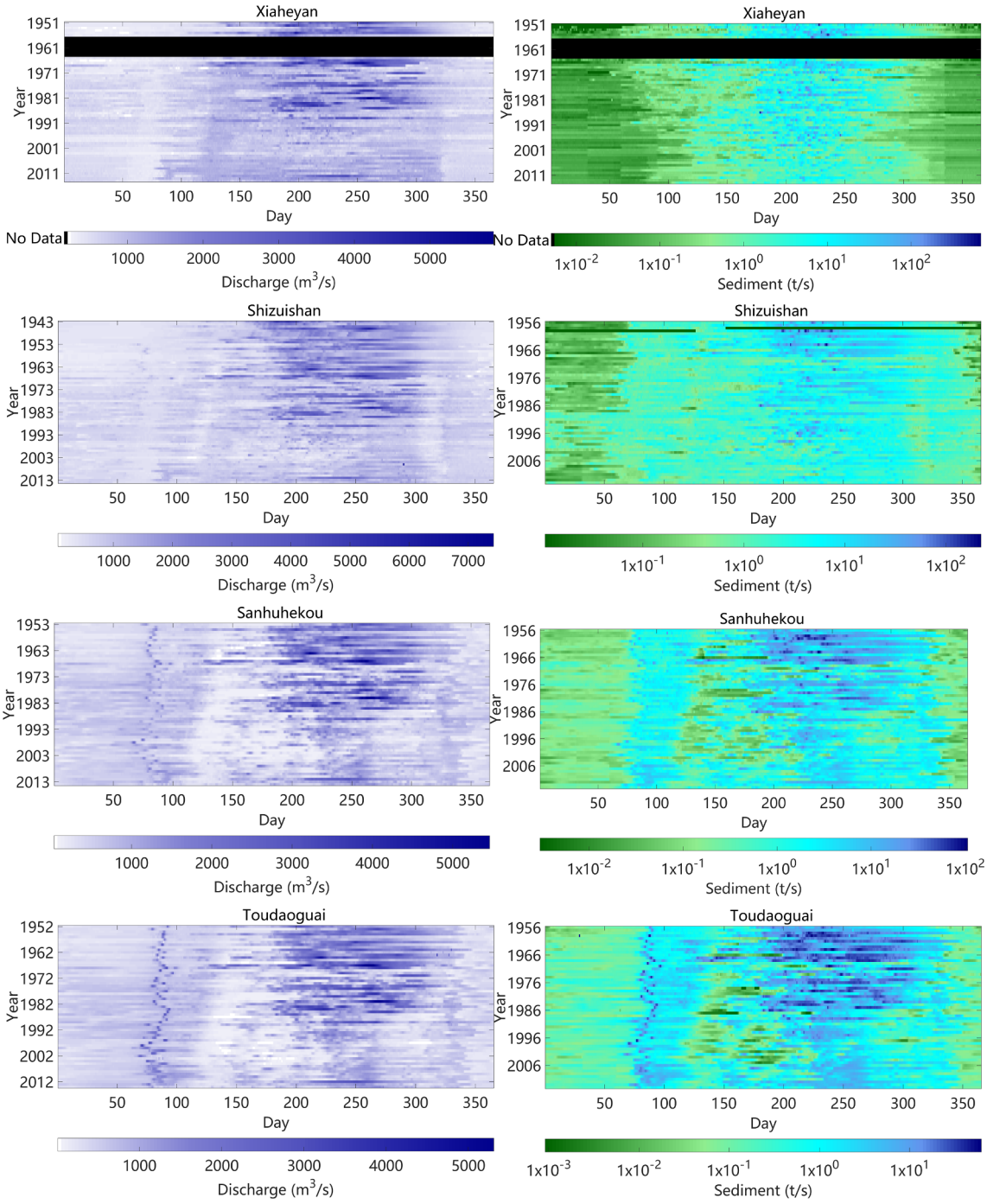

Fig. 2. Daily datasets of runoff and sediment loads at representative stations.

(3) Periodicities in the measured runoff and sediment load datasets

The multiple-timescale periodicities of the runoff and sediment loads were obtained from complex Morlet wavelet analyses. The real parts of the wavelet coefficient are shown in the contour maps of Fig. 5. Whereas Fig. 6 shows a wavelet variance, indicating the magnitude of periodic fluctuation within the time series. It is easy to locate the dominant periods with the help of a wavelet variance plot (Yang, 2001; Miao et al., 2011). The series of runoff and sediment loads in the upper Yellow River comprised several periods at different time scales. Furthermore, the oscillation centers of various time scales formed interlacing positive and negative contours. The average of annual runoff and sediment loads during 1950–2010 were chosen as the reference plane. Thus, the magnitudes (positive or negative) of the real part of the wavelet coefficient in the contour maps reflect the plentiful or low flow areas within the time scale. The runoff and sediment load series from the four stations exhibit obvious inter-year and inter-decade changes.

According to Figs. 5 and 6, the periodic behaviors and durations are identified in Table 4. In the recorded period, the annual runoff of the upper Yellow River showed four periodicities: 4-a, 8-a, 16-a, and 25 or 27-a. The dominant runoff periodicity was 27-a for the Sanhuhekou station and 25-a for the other stations. The annual sediment load showed periodicities of 3-a, 4-a, 8-a, 9-a, 11-a, 22-a, and 24-a, with the dominant periodicity of 24-a for the Toudaoguai and 22-a for the other stations. Water diversion played a role in influencing the periodicities of runoff and especially sediment load. The intensive water diversion

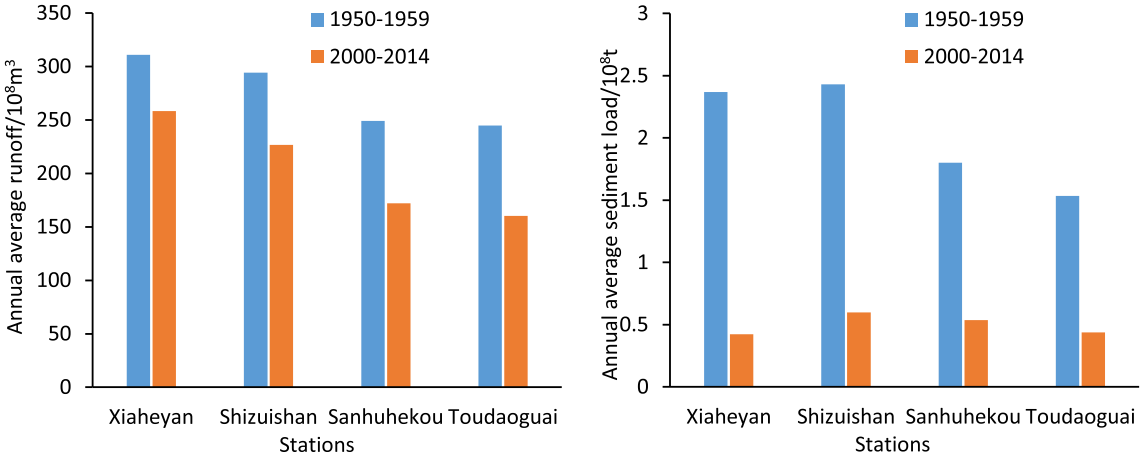

Fig. 3. Annual average runoff (left) and sediment loads (right) of Xiaheyan, Shizuishan, Sanhuhekou, and Toudaoguai stations.

between Shizuishan and Sanhuhekou altered the runoff at the Sanhuhekou station. Some of the diverted water was discharged back into the reach between Sanhuhekou and Toudaoguai, and the runoff at Toudaoguai was less affected compared to the upper stations.

(4) Comparison of the measured and reconstructed runoff series

The reconstructed annual runoff series based on the modeling scenario of removing the impacts of reservoir impoundment and water diversion for agriculture irrigation and urban industry for the period of 1956–2000, are plotted in Fig. 7. The reconstructed runoff series are assumed to be ones under natural condition undisturbed by human activities. Apart from the measured datasets, the reconstructed runoff did not change significantly during the studied period. The results of MK testing and wavelet analysis for the reconstructed runoff series are shown in Fig. 8. The *Z* values of the MK test for the reconstructed runoff are all only about 1/3 of the corresponding values of the measured runoff (Fig. 8 and Tables 2 and 5). The natural runoff was stable and rarely changed over the past 50 years when no human interference was found. Additionally, the dominant periodicity of the reconstructed runoff was found between 26- to 31-a, longer than that of the measured datasets. However, the short periodicities were 5-, 7-, and 11-a, which were shorter than those of the measured values. This indicates that human disturbance has shortened the period of low frequency flood, while elongating the period of high-frequency runoff on the upper Yellow River. Changes in the wavelet variance indicate that the short periodicities are more intensively disturbed compared with long periodicities.

4. Discussion

In the context of global warming and intensified human perturbations, sustainable river management requires understanding the variation mechanisms of flow regimes and flooding. Therefore, investigations of regional and global hydrological changes and their subsequent impacts on society have received considerable attention in recent years considering cropland expansion and urbanization, water consumption for human use, and river-damming. All of these things alter natural flow and sediment movement in river channels across the aquatic ecosystem (Wang et al., 2007). In this study, the upper Yellow River was investigated to illustrate the inter-annual and monthly variations in runoff and sediment loads, and to reveal the impact of basin-wide human activities on those variations. Our study methods and the perspectives of analyses used are good references for future investigations of other large river basins.

Table 3
Results of abrupt change test for the time series of runoff and sediment loads for the representative stations.

Stations	Abrupt changing year of annual runoff	Abrupt changing year of annual sediment load	Confidence level
Xiaheyan	1986	1989	0.05
Shizuishan	1986	1986	0.05
Sanhuhekou	1986	1978	0.05
Toudaoguai	1986	1982	0.05

(1) Multiple stresses influencing the hydrological features of the upper Yellow River

The Yellow River basin has experienced multiple stresses, and the hydrological features have been remarkably altered, resulting in the deterioration of its ecological environment. Thus, scientists have been concerned for decades (Wang et al., 2016). Datasets from gauge stations have been widely used to elucidate hydrological variations along the Yellow River. Implications have been made based on sparsely distributed gauge stations. Wang et al. (2007) used measured data from 1950 to 2005 at four gauge stations, two upstream and two downstream, to elucidate the decreases of sediment load to the river mouth. From this perspective, more careful and detailed recognition in

Table 2
Variation trends in the time series of runoff and sediment load for the representative stations indicated by the MK trend test.

Stations	Annual runoff			Annual sediment			Runoff in flood season			Sediment in flood season		
	Z	*P*	Tr	*Z*	*P*	Tr	*Z*	*P*	Tr	*Z*	*P*	Tr
Xiaheyan	−3.06	0.002	↓	−6.14	< 0.001	↓	−4.51	< 0.001	↓	−5.79	< 0.001	↓
Shizuishan	−3.44	< 0.001	↓	−5.10	< 0.001	↓	−4.79	< 0.001	↓	−5.34	< 0.001	↓
Sanhuhekou	−3.65	< 0.001	↓	−4.61	< 0.001	↓	−4.82	< 0.001	↓	−5.21	< 0.001	↓
Toudaoguai	−3.73	< 0.001	↓	−5.39	< 0.001	↓	−4.88	< 0.001	↓	−5.63	< 0.001	↓

Note: *P*: confidence value; Tr: trend; ↓ indicates significantly decreasing trend.

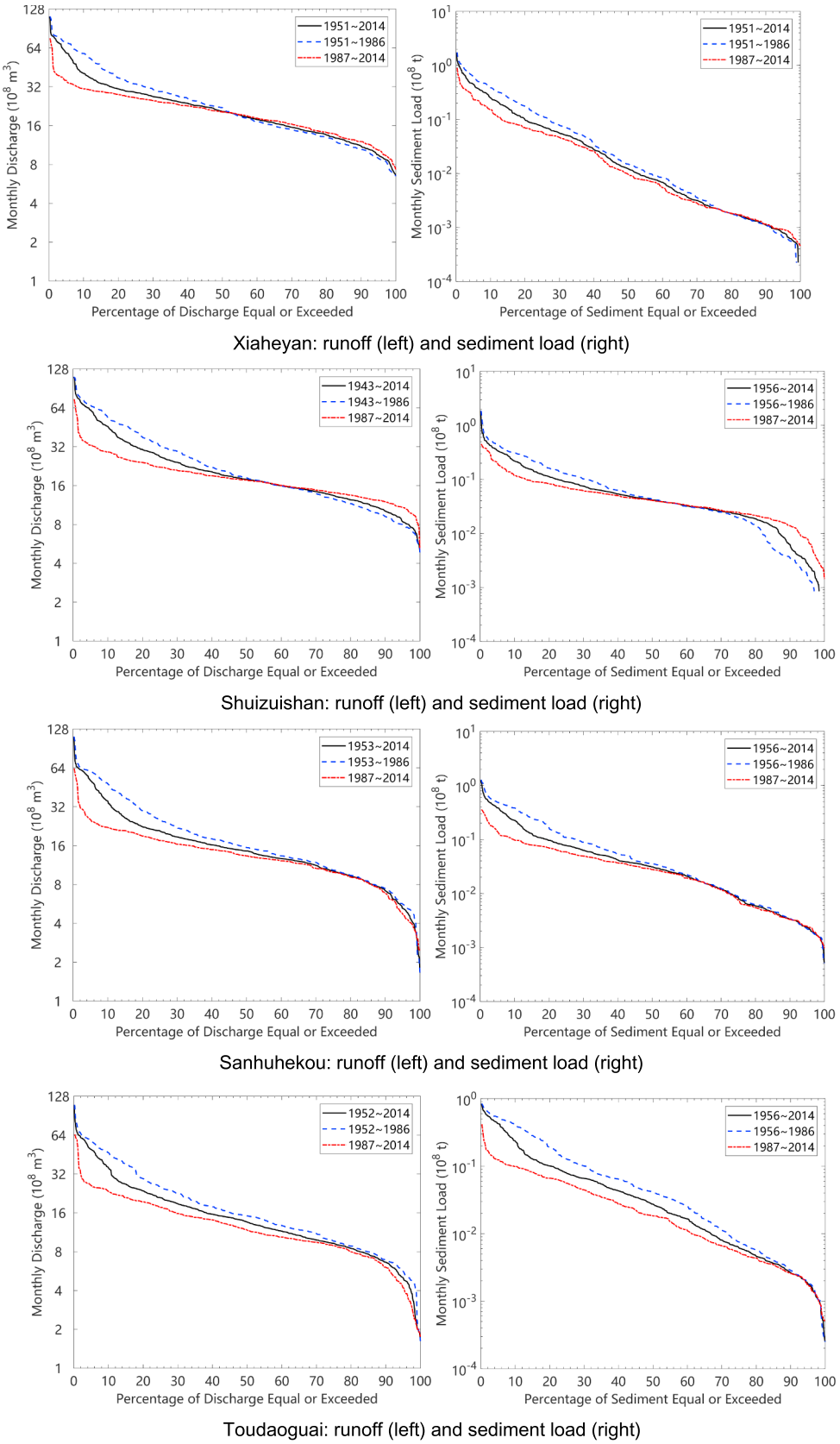

Fig. 4. Hydrographs before and after the abrupt changes at Xiaheyan, Shizuishan, Sanhuhekou, and Toudaoguai stations.

hydrological variations of the upper Yellow River are given, based on more integral observations and comparison with modeling.

Anthropic activities, including elevated water consumption and hydropower exploitation, are among the main stresses. As of 2014, over 25 large reservoirs, with capacities > 100 million m^3, have been constructed on the stem. Soil conservation projects, including enormous check dams, terraces, and reforestation projects, have played important roles in changing runoff and sediment loads. There has been much

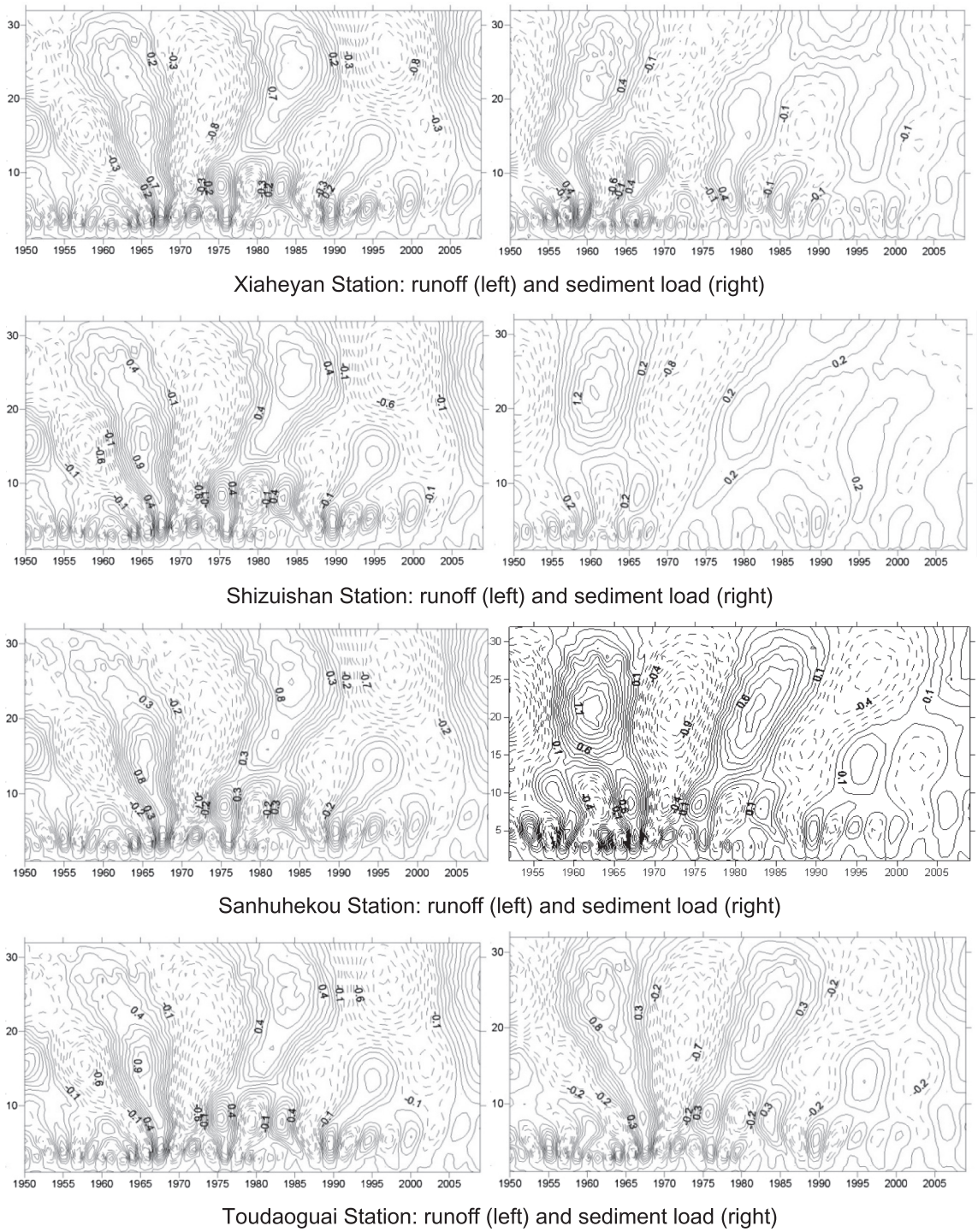
Xiaheyan Station: runoff (left) and sediment load (right)
Shizuishan Station: runoff (left) and sediment load (right)
Sanhuhekou Station: runoff (left) and sediment load (right)
Toudaoguai Station: runoff (left) and sediment load (right)

Fig. 5. Contour maps of the real parts of wavelet coefficients for the annual runoff (left) and sediment load (right) at the Xiaheyan, Shizuishan, Sanhuhekou, and Toudaoguai Stations. The horizontal ordinate of the map represents years, and the vertical coordinate represents the time scale. The digital values in the plots indicate the real parts of the wavelet coefficient, which reveal the periodical features of the hydrological series (e.g., the positive values indicating wet periods while the negative values indicating dry periods, and the largest absolute value indicating the periodical duration).

interest in these rapid changes in the Yellow River basin, especially in the middle and lower reaches (Yang et al., 1998; Walling and Fang, 2003; Syvitski et al., 2005; Wang et al., 2016). Both human activities and climatic changes are regarded as essential driving forces for these changes. The operation of reservoirs has changed seasonal and inter-annual allocations of water discharge and has facilitated a rapid increase in water consumption, particularly in the lower reaches (Wang et al., 2007). A rough estimation for the Loess Plateau suggest that 30% of the decrease in sediment load has resulted from climate change (i.e., decrease of precipitation) and 70% from human activities, resulting in channel scouring of the lower reaches, instead of severe flooding deposition that had been characteristic of the period prior to implementation of the Water Sediment Regulation Scheme (Wang et al., 2007).

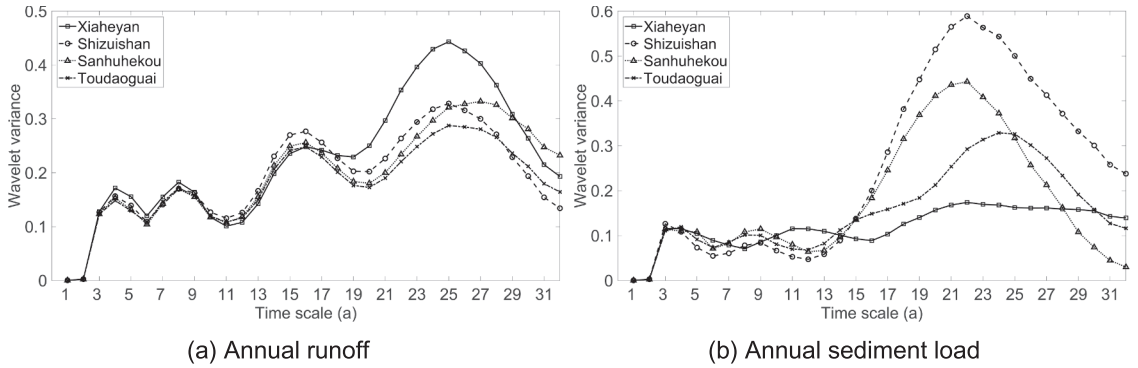

Fig. 6. Wavelet variance graphs for the measured datasets of the Xiaheyan, Shizuishan, Sanhuhekou, and Toudaoguai Stations.

Table 4
Multi-periodicities of the measured annual runoff and sediment load.

Stations	Annual runoff		Annual sediment load	
	Multiple time-scale periodicity (a)	Dominant periodicity (a)	Multiple time-scale periodicity (a)	Dominant periodicity (a)
Xiaheyan	25; 16; 8; 4	25	22; 11; 4	22
Shizuishan	25; 16; 8; 4	25	22; 9; 3	22
Sanhuhekou	27; 16; 8; 4	27	22; 9; 3	22
Toudaoguai	25; 16; 8; 4	25	24; 8; 4	24

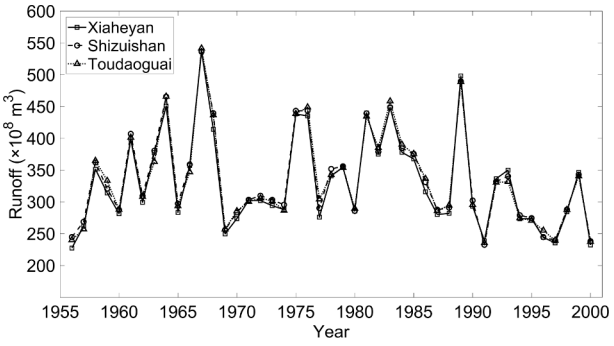

Fig. 7. Reconstructed time series of runoff for the Xiaheyan, Shizuishan, and Toudaoguai stations.

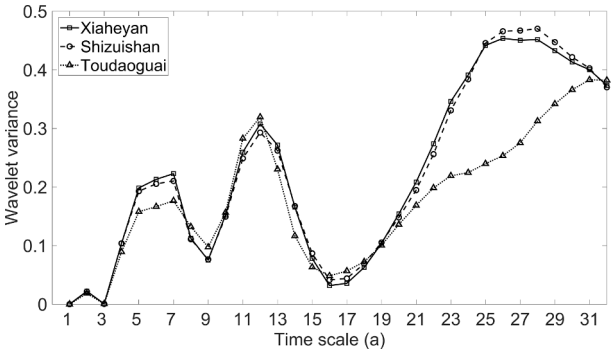

Fig. 8. Wavelet variance graphs of the reconstructed time series of runoff.

(2) Trends of Variations in runoff and sediment load in the upper Yellow River

Previous studies mainly focused on hydrological trends at a limited number of stations, emphasizing the attributions for runoff and sediment load variations mainly for middle and lower reaches of the Yellow River. Neither of the variations, in terms of abrupt changes or periodical features for the runoff and sediment load series, were considered for the upper Yellow River: the major runoff-producing region. A detailed assessment of the variations in runoff and sediment load of the upper Yellow River presented in this study helps clarify the changes in water and sediment load discharges and their attributions. The results of this study show significant decreasing trends in both annual runoff and sediment loads. The year 1986 was identified as the abrupt changing year of runoff in this study period.

Slightly decreasing or non-significant upward trends in annual precipitation and significant increases in air temperature were detected in this region (Zhang et al., 2013; Zuo et al., 2016; Kong et al., 2018). Adding the regional dry climate and high evaporation, climate change could result in a slight, but not considerable, change in runoff. The assumed natural runoff series reconstructed by removing the influence of impoundment and water diversion in this study indicates that influences of human activities played a dominant role in hydrological variations. The reconstructed runoffs regarded as only affected by climate change showed no significant changing trend at a 95% confidence level, confirming that, instead of climate change, human activities played the most important roles in variations. A complex wavelet analysis and MK tests revealed that reservoir impoundment and water diversion shortened the period of low-frequency flood, but elongated the period of high frequency runoff in the upper Yellow River.

Water conservation projects targeting water and sediment yield tributaries of the upper Yellow River have caused marked changes in the discharges of runoff and sediment. Considering the major tributaries Zulihe, Qingshuihe, Kushuihe, and the ten Kongduis (small rivers formed by ice flows), the annual runoff from these tributaries to the stem increased from 340 million m^3/yr from 1955 to 1989 to 440 million m^3/yr from 1990 to 2009, whereas the annual sediment load from these tributaries to the stem decreased from 96.2 to 78.9 million tons/yr for those two periods (Zhang et al., 2013).

Moreover, the completions and joint operations of the Yanguoxia, Qingtongxia, and Sanshenggong reservoirs on the upper Yellow River since the 1960 s (i.e., the Liujiaxia in 1968 and the Longyangxia in 1985) showed extended discontinuous runoffs and sediment processes. Wang et al. (2007) showed that the runoff and sediment discontinuity years correlated to reservoir operation years. The joint operation of Longyangxia and Liujiaxia reduced the flow discharge of the flood season and increased the non-flood season runoff. Moreover, the duration of flood discharges at 2000 m^3/s at the Toudaoguai station decreased from 32.2 to 2.4 days, owing to joint operations in 1986 (Shang et al., 2008). Sediment trapped in the upstream reservoirs Longyangxia, Liujiaxia, Yanguoxia, Bapanxia, Qingtongxia, and Sanshenggong reached to 2.11 billion m^3 from 1960 to 1989 and 800 million m^3 from 1990 to 2003, significantly reducing the sediment load downstream (Zhang et al., 2013). The reservoirs on the upper Yellow River have strongly altered the regime and magnitude of streamflow and have trapped large amounts of sediment, leading to severe siltation and stepwise reduction of the total volumes (Zhao et al., 2014).

Table 5
Multiple time-scale features of the reconstructed time series of runoff.

Stations	Annual runoff			Periodicity	
	Z	*P*	Tr	Multiple time-scale periodicity	Dominant periodicity
Xiaheyan	−1.26	0.2	Non-significant	7; 12; 26	26
Shizuishan	−1.46	0.1	Non-significant	7; 12; 28	28
Toudaoguai	−1.46	0.1	Non-significant	7; 12; 31	31

Large irrigation zones with an effective irrigation area of up to 1 million hm^2 have caused remarkable reductions of water and sediment loads in the upper Yellow River. The annual water consumption by irrigation zones was near 7.88 billion m^3/yr, accompanying a sediment load reduction of 30.4 million tons/yr from 1952 to 1989, with an increased annual water consumption and annual sediment load reduction by 18% and 8%, respectively, from 1990 to 2004 (Zhang et al., 2013). The evolution of channel beds has also impacted the variation in sediment loads downstream. About 410 million tons of sediment were deposited on the channel of the Inner Mongolia stretch from 1962 to 1991 with 14 million tons deposit per year, and the aggradation aggravated remarkably since with 841.6 million tons deposit from 1991 to 2004, corresponding to an annual deposit of 64.7 million ons/yr (Zhang et al., 2013).

Consequently, the abrupt changing trends and periodicities of the time series of runoff and sediment load are disorderly and asynchronous, indicating complicated influences to the fluvial processes over time. On one hand, most sediment was trapped in reservoirs during impoundment. On the other hand, the downstream reach channel was also scoured, owing to the low sediment loaded discharge from of the reservoirs, altering the variation features of sediment load. Soil conservation practices in the upper tributaries changed the natural processes of rainfall-runoff-sediment yields, causing the sediment load variation features to not coincide with the runoff.

5. Conclusions

This study analyzed variations in runoff and sediment loads on the upper Yellow River, based on updated datasets of hydrological stations from the past 65 years. Changing trends, abrupt change years, and multi-periodicities were discerned from the time series. The impact of human activities on hydrological characteristics was evaluated, based on comparison of the measured and reconstructed time series. This indicated that the combined impact of lower precipitation and intensive human activities, including soil conservation practices, water and sediment retention within reservoirs, water abstraction, and sedimentation in channel beds, resulted in distinct stepwise decreases in the runoff and sediment loads discharged from the upper Yellow River. Runoff and sediment load variations were disorderly and asynchronous, causing complicated influences to the fluvial processes for a long time. The knowledge obtained from this study can provide useful information for water resource planning, management, and soil and water conservation in the upper Yellow River, ostensibly aiding predictions of runoff and sediment load variations in the lower reach.

Author Contribution Statement

Shimin Tian collected and analyzed data and wrote the first version of the manuscript. Mengzhen Xu conceived and designed the study, and revised the manuscript. Enhui Jiang gave valuable suggestions on the data analysis. Guanghui Wang helped data proceeding and drew some of the figures. Hongchang Hu helped with data analysis. Xing Liu helped with the data collection and proceeding.

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References

An, C.H., Lu, J., Qian, Y., Luo, Q.S., Cui, Z.H., 2018. Spatial-temporal distribution characteristic and course of sedimentation in the ningxia-inner mongolia reaches of the yellow river. Shuili Xuebao 49 (2), 195–215 (in Chinese with English Abstract).
Benson, N.C., Daggett, V., 2012. Wavelet analysis of protein motion. Int. J. Wavelets Multiresolut. Inform. Process. 10 (4), 1250040.
Burn, D.H., Hag Elnur, M.A., 2002. Detection of hydrologic trends and variability. J. Hydrol. 255 (1), 107–122.
Chattopadhyay, G., Chakraborthy, P., Chattopadhyay, S., 2012. Mann-kendall trend analysis of tropospheric ozone and its modeling using ARIMA. Theor. Appl. Climatol. 110, 321–328.
Chen, J., Wang, F., Meybeck, M., He, D., Xia, X., Zhang, L., 2005. Spatial and temporal analysis of water chemistry records (1958–2000) in the Huanghe (Yellow River) basin. Global Biogeochem. Cycles. 19, GB3016.
Dziedziech, K., Staszewski, W.J., Uhl, T., 2015. Wavelet-based modal analysis for time-variant systems. Mech. Syst. Sig. Process. 50–51, 323–337.
Hamed, K.H., 2009. Exact distribution of the Mann-Kendall trend test statistic for persistent data. J. Hydrol. 365 (1), 86–94.
He, B., Miao, C.Y., Shi, W., 2013. Trend, abrupt change, and periodicity of streamflow in the mainstream of Yellow River. Environ. Monit. Assess. 185, 6187–6199.
Hirsch, R.M., Smith, R.A., Slack, J.R., 1982. Techniques of trend analysis for monthly water quality data. Water Resour. Res. 18 (1), 107–121.
Issac, M., Renuka, G., Venugopal, C., 2004. Wavelet analysis of long period oscillations in geomagnetic field over the magnetic equator. J. Atmos. Sol. Terr. Phys. 66, 919–925.
Kendall, M.G., 1975. Rank Correlation Methods. Griffin, London.
Kong, D.X., Miao, C.Y., Borthwick, A.G.L., Lei, X.H., Li, H., 2018. Spatiotemporal variations in vegetation cover on the Loess Plateau, China, between 1982 and 2013: possible causes and potential impacts. Environ. Sci. Pollut. Res. https://doi.org/10.1007/s11356-018-1480-x.
Labat, D., 2005. Recent advances in wavelet analyses: Part 1. A review of concepts. J. Hydrol. 314 (1–4), 275–288.
Labat, D., Ronchail, J., Guyot, J.L., 2005. Recent advances in wavelet analyses: part 2 – Amazon, parana, orinoco and congo discharges time scale variability. J. Hydrol. 314 (1–4), 289–311.
Mann, H.B., 1945. Nonparametric tests against trend. Econometrica 13 (3), 245–259.
Miao, C.Y., Yang, L., Liu, B.Y., Gao, Y., Li, S.L., 2011. Streamflow changes and its influencing factors in the mainstream of the Songhua River basin, Northeast China over the past 50 years. Environ. Earth Sci. 63 (3), 489–499.
Nakken, M., 1999. Wavelet analysis of rainfall–runoff variability isolating climatic from anthropogenic patterns. Environ. Modell. Softw. 14, 283–295.
Neeti, N., Eastman, J.R., 2011. A contextual Mann-Kendall approach for the assessment of trend significance in image time series. Trans. GIS 15 (5), 599–611.
Nishioka, M., Takara, K., 2004. A trend analysis of hydrological time series by Mann-Kendall test. J. Jpn Soc. Hydrol. Water Resour. 17 (4), 343–353.
Shadmani, M., Marofi, S., Roknian, M., 2012. Trend analysis in reference evapotranspiration using Mann-Kendall and Spearman's Rho tests in arid regions of Iran. Water Resour. Manage. 26 (1), 211–224.
Shang, H.X., Zheng, Y.S., Zhang, X.H., 2008. Influence of reservoir operation to the silt-discharge condition of ning-mong section of the yellow river. Yellow River 30 (12), 28–31 (in Chinese with English Abstract).
Shen, G.Q., Zhang, Y.F., Hou, S.Z., Shang, H.X., 2007. Impact of water and sediment regulation by reservoirs in the upper Yellow River on Inner-Mongolia reaches. J. Sedim. Res. 1, 67–75 (in Chinese with English Abstract).
Smith, L.C., Turcotte, D.L., Isacks, B.L., 1998. Streamflow characterization and feature detection using a discrete wavelet transform. Hydrol. Process. 12, 233 ± 249.
Syvitski, J.P.M., Kettner, A.J., Overeem, I., Hutton, E.W.H., Hannon, M., Brakenridge, R., Day, J., Vörösmarty, C., Saito, Y., Giosan, L., Nicholls, R.J., 2009. Sinking deltas due to human activities. Nat. Geosci. 2, 681–686.
Syvitski, J.P.M., Vörösmarty, C.J., Kettner, A.J., Green, P., 2005. Impact of humans on the flux of terrestrial sediment to the global coastal ocean. Science 308 (5720), 376–380.
Tian, S.M., Deng, C.X., Xie, B.F., Zhang, X.H., 2013. Effects of joint operation of the

longyangxia and liujiaxia reservoirs on scouring and sedimentation of the ningxiainner mongolia reach. Adv. Sci. Technol. Water Resour. 33 (3), 59–63 (in Chinese with English Abstract).
Walling, D.E., 2006. Human impact on land-ocean sediment transfer by the world's rivers. Geomorphology 79 (3–4), 192–216.
Walling, D.E., Fang, D., 2003. Recent trends in the suspended sediment loads of the world's rivers. Global Planet. Change 39 (1–2), 111–126.
Wang, H.J., Yang, Z.S., Saito, Y., Liu, J.P., Sun, X.X., Wang, Y., 2007. Stepwise decreases of the Huanghe (Yellow River) sediment load (1950–2005): impacts of climate change and human activities. Global Planet. Change 57 (3–4), 331–354.
Wang, S., Fu, B.J., Piao, S.L., Lü, Y.H., Ciais, P., Feng, X.M., Wang, Y.F., 2016. Reduced sediment transport in the Yellow River due to anthropogenic changes. Nat. Geosci. 9, 38–41.
Williams, M., 2012. River sediments. Philos. Trans. R. Soc. 370, 2093–2122.
Yang, Z.S., Milliman, J.D., Galler, J., Liu, J.P., Sun, X., 1998. Yellow River's water and sediment discharge decreasing steadily. Eos 79 (48), 589–592.
Yao, W.Y., Zhang, X.H., Gao, Y.J., Jiao, P., 2017. Features of runoff and sediment variations in wide-valleyed desert reach of upper yellow river and contribution rate of driving factors for the variations. J. Desert Res. 37 (2), 361–371 (in Chinese with English Abstract).
Zhang, S.W., Ding, J., Liao, J., Zhang, X.C., Wang, L., 2004. Analysis of natural annal flow time seris in the upper reach of the yellow river based on wavelet transform. J. Sichuan Univ. (Eng. Sci. Edn.) 36 (3), 32–37 (in Chinese with English Abstract).
Zhang, X.H., Su, X.H., Zheng, Y.S., Tian, S.M., 2013. Features and trends of recent changes in runoff and sediment regimes in wide-valleyed desert reach of Upper Yellow River. J. Sedim. Res. 2, 44–51 (in Chinese with English Abstract).
Zhao, G., Mu, X., Strehmel, A., Tian, P., 2014. Temporal variation of streamflow, sediment load and their relationship in the yellow river basin China. PloS ONE 9 (3). https://doi.org/10.1371/journal.pone.0091048. e91048.
Zuo, D.P., Xu, Z.X., Yao, W.Y., Jin, S.Y., Xiao, P.Q., Ran, D.C., 2016. Assessing the effects of changes in land use and climate on runoff and sediment yields from a watershed in the Loess Plateau of China. Sci. Total Environ. 544, 238–250.